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Jian Xue

Katherine Linville

Yu Li

Pranav Nitin Godse
Missouri University of Science and Technology

et. al. For a complete list of authors, see https://scholarsmine.mst.edu/engman_syseng_facwork/826

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RISK AWARENESS ENHANCEMENT SYSTEMS FOR HAZMAT TRANSPORTATION: PROTOTYPING AND TECHNOLOGY EVALUATION

Jian Xue, Katherine Linville, Yu Li, Pranav Nitin Godse, Suzanna Long and Ruwen Qin
Missouri University of Science and Technology
qinr@mst.edu

Jian Xue, Jihong Yan and Lizhong Zhao
Harbin Institute of Technology
18s008105@stu.hit.edu.cn

Abstract
Workers of hazardous material (hazmat) transportation have a higher chance than other workers to be exposed to various risks in their workplace. Assisting them to safely operate in their workplace in a near real-time manner is in particular need. This paper presents a study of designing, prototyping and developing feedback systems to help increase the risk awareness of workers in the loading and uploading phases of hazmat transportation. The first system was prototyped on an Arduino board, serving as the reference for system development. Then, the second system, named a Bluetooth Low Energy (BLE) beacon based system, was designed as a smart connected system. It integrated technologies of Bluetooth low energy sensor, mobile smart device, the Cloud, wireless communication, and mobile applications. The smart connected system is more capable than the Arduino based system in providing safety information to workers. A comparison of the respective technologies utilized in the two systems further indicates that the improved capability of the smart connected system is mainly on the dimensions of interactivity, mobility, information richness, and connectivity.

Keywords
Hazardous material, safety, transportation workers, smart connected systems, cyber-physical systems

Introduction
In the United States, there are more than 800,000 hazardous material (hazmat) shipments per day (Lasisi, Bai, & Sun, 2012). Hazmat transportation research has various focuses. For example, an Integrated Emergency Management System for hazmat transportation was developed in order to address the issue of insufficient information sharing among transport companies, drivers and government agencies (Ma, Wang, Lu, & Jiang, 2014). The safety of hazmat transportation has been a particularly important subject of study. For example, a system was developed to help minimize the impact to first responders' health in a hazmat transportation incident (Fruhling, Achutan, Medcalf, & Yoder, 2018). Workers of hazmat transportation have a higher chance than other workers to be exposed to various risks in their workplace (Incident Statistics, 2018). Many studies on the safety of hazmat transportation workers are mainly focused on the in-transit phase. Top reasons for hazmat incidents during this stage largely overlap with those in moving other goods and passengers. A large portion of the incidents in transporting hazmat has occurred due to human error, particularly during the loading and unloading phases of transportation (Bureau of Transportation Statistics, 2017; Godse, Long, Qin, & Xue, 2018). The economic, social, and environmental consequences of the incidents are traditionally severe in nature (Office of Hazardous Materials Safety, 2017). Protecting transportation workers from these potential risks and improving their ability to operate safely in their workplace is important. For example, drivers transporting hazmat must receive initial and recurring trainings on general awareness and familiarization of hazmat, safety training on emergency response, and measurements to protect themselves from exposure to the hazmat (An Overview of 49 CFR parts 172-173, 2019). Well-trained transportation workers may still make mistakes that cause exposure to risks in their respective workplaces. Some of the leading factors are that human beings have bounded abilities in vision, cognition, making a judgment, and simultaneously handling multiple tasks, particularly in complex, dynamic working environments, or in response to suddenly occurred situations. Improving their ability to safely operate in their workplace through assisting them from various needed aspects in a near real-

time manner is in particular need (Mendez et al., 2015). We were motivated to seek ways of assisting transportation workers.

Providing timely, appropriate feedback to workers to enhance their awareness of risks, or providing operations guidance when needed, would reduce the chance of them being involved in or causing incidents. The rapid development of sensor technologies, data processing methods, control theory, and systems science has promoted the growth of cyber-physical systems (CPSs) (Kim & Kumar, 2012; Sha, Gopalakrishnan, Liu, & Wang, 2008). CPSs synergize those capabilities to create new or larger capabilities to facilitate various industries including transportation (Khaitan & McCalley, 2015). The feedback system is a necessary component of a CPS, which let the cyber system communicate with the physical system. Therefore, the capability and effectiveness of the feedback system are critical to a CPS. This paper presents a study of developing feedback systems for enhancing the risk awareness of workers, particularly in the loading and unloading phases of hazmat transportation. From the study, we aim to thoroughly understand the role of the underlying technologies in a smart connected feedback system.

The remainder of the paper is organized as follows. The next section presents a feedback system that we rapidly prototyped. It served as a reference for the smart connected feedback system described in the third section. We compare the two systems in terms of the technologies they use in the fourth section and, accordingly, conclude the study in the last section.

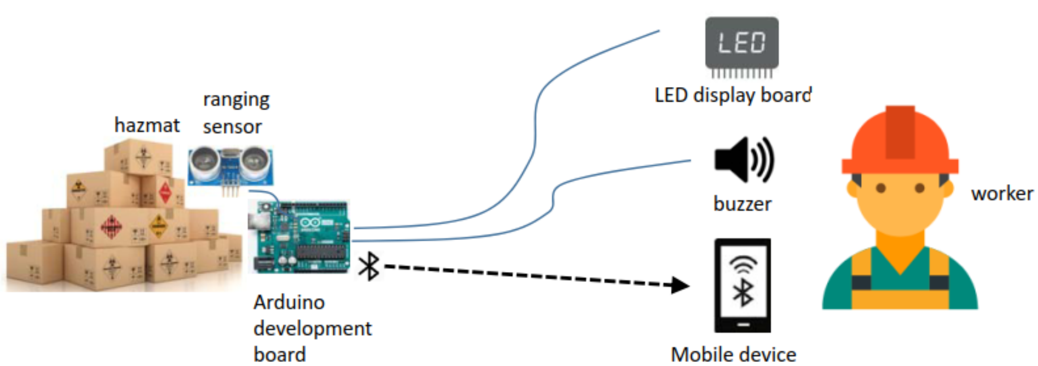
The Arduino Based System

We first designed an Arduino based system. It was rapidly built and served as a reference system of the study.

System Architecting

The Arduino based system, as illustrated in Exhibit 1, is composed of an Arduino development board, a ranging sensor, and one or multiple feedback devices. The ranging sensor is attached to the Arduino board and the board is with the hazmat. Brief safety information of the hazmat has been saved in the board. When a worker enters a zone near the hazmat, which is defined by specifying the detectable range of the ranging sensor, either the safety information is displayed on a displaying device or an alarm is provided by the buzzer.

Exhibit 1. Schematic Diagram of the Arduino Based Feedback System



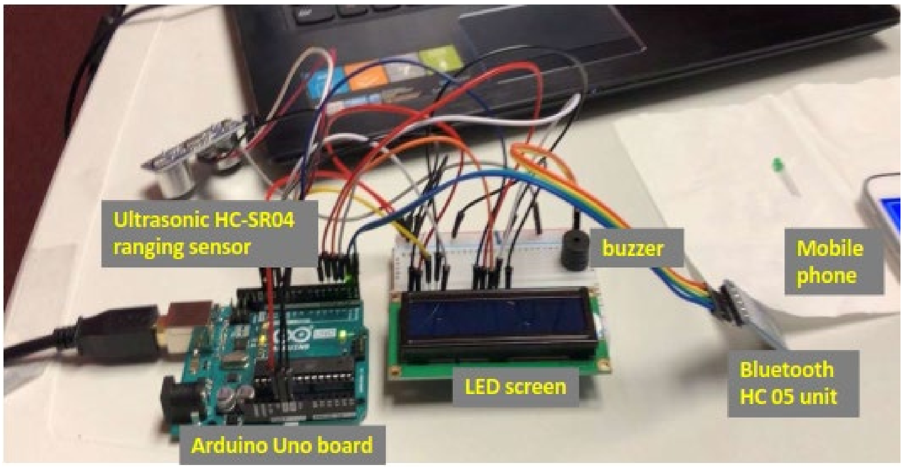
System Prototyping

The Arduino based system is displayed in Exhibit 2. We chose Arduino Uno that is the best board to get started with electronics and code the output displayed on receiving devices. The ultrasonic sensor HC-SR04 was chosen, which provides from 2 cm to 400 cm non-contact measurement function with the precision up to 0.3 cm. Receiving devices are used for either visually displaying safety information or broadcasting alarming sound to workers. We tested three types of receiving devices: a buzzer, a Light Emitting Diode (LED) display board, and a smart mobile phone. A Bluetooth HC-05 unit was used to transmit the safety information to the mobile phone of the worker. As Exhibit 2 shows, the buzzer, LED screen, and the Bluetooth unit are connected to the Arduino board using wires.

We used the open-source Arduino software, IDE, to code functions and upload the code to the board. The language we used to compile the code is C. The board was firstly programmed to be able to trigger the buzzer, display a message on the LED screen, or transmit the message to the mobile phone through the Bluetooth unit when the worker enters a pre-specified detectable range of the ranging sensor. Then, the board was connected to the computer to get the complied program uploaded.

While the Arduino based system was easily built and successfully provides the basic feedback function, limitations are clearly found. This system is restricted by the limited safety information that can be provided, the very simple feedback mechanism that can be used, and the lack of mobility of some receiving devices. These motivated the development of a smart connected feedback system.

Exhibit 2. The Prototype of the Arduino Based System



The BLE Beacon based System

To address the limitations of the Arduino based system, the study designed a smart connected feedback system that replaced the ultrasonic sensor with a Bluetooth Low Energy (BLE) beacon and used only a smart mobile phone as the receiving device.

System Architecting

The BLE beacon based system, illustrated in Exhibit 3, is composed of three components: a BLE proximity sensor, the safety information, and a mobile device being used by the worker which can receive the information. The sensor is physically attached to or within a short range of the hazmat. The sensor attached to the hazmat is associated with the safety information of the material through the cloud management system of the sensor. When a worker with an associated mobile device enters the defined broadcast range of the proximity sensor, the sensor detects the worker and pushes the safety information to the receiving device. The respective hazmat class safety information is then either presented in a push notification or as a message within the application. By reviewing the provided information, the worker's awareness of the hazmat, potential risks of transporting the material, and safety guidelines related to the material in question are reinforced.

System Prototyping

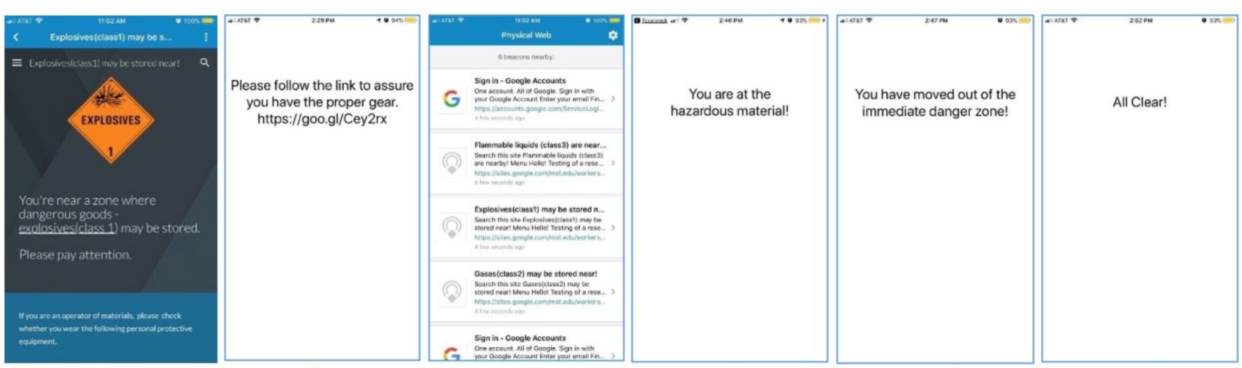
We developed two versions of safety information: detailed information and brief targeted information. We presented the detailed information of each class of hazmat as a webpage illustrated in Exhibit 4(a). The webpage includes (i) key alarm message, (ii) check list of required personal protection equipment, and (iii) specific information of material belonging to the class. A link to part (iii) is embedded in the statement of part (i). Workers who are not familiar with, or cannot recognize, the nature of the hazmat in question are able to jump to this section quickly through the provided link in the first section.

The Uniform Resource Locator (URL) of a webpage is the reference address that identifies where the webpage is located on the Internet. The URL is pushed to the receiving device of the worker through a mobile app. Exhibit 4(b) displays the notification of the webpage URL, which is generated by a mobile app we developed. Exhibit 4(c) is the nearby notification generated by Physical Web, an app provided by Google.

If workers choose to not click the link to the webpage, they will not be shown the safety information provided on the webpage. Therefore, an alternative approach is to directly present brief targeted safety information as alerts and push the alerts to the mobile app on the receiving devices of workers. Exhibit 4(d-e) illustrates three notifications displayed by the mobile app in the receiving device.

Exhibit 3. Schematic Diagram of the BLE Based Feedback System

Exhibit 4. Safety Information: (a) the webpage, (b) in app notification containing the webpage URL, (c) Physical Web nearby notification, and alerts (d) when entering the inner zone of hazmat, (e) leaving the inner zone, and (f) leaving the outer zone



(a) (b) (c) (d) (e) (f)

The BLE proximity sensor we chose was the proximity beacons produced by Estimote®. A beacon is a tiny device that broadcasts Bluetooth data packets understood by compatible receiving devices. The data packets contain the unique identity of the beacon and other necessary data. Beacons broadcast them with a certain strength in all possible directions. Therefore, we selected and defined distances for receiving specific data packets. For example, when a worker with a mobile receiving device enters a zone defined by a distance we selected, a corresponding beacon packet is sent to the designated mobile app installed on the receiving device. When a beacon packet is received, the app is immediately made aware of its arrival. A request is then sent to the Estimote Cloud for further instruction on what to do about this particular beacon. The Cloud returns the necessary information in milliseconds and the app performs the programmed activity, which in this app is to display an alert. Settings of the beacons are managed in the Estimote Cloud.

A beacon needs to be connected to a mobile app that performs designed activities to interact with workers. We both developed our own IOS app and used a third-party app named Physical Web provided by Google. Physical Web can receive URL messages sent by beacons as shown in Exhibit 4(c), but it is also able to detect Bluetooth signals of other types of nearby devices. If there were a large number of other detectable devices in the application environment, it would have a substantial impact on beacon users.

The app we developed can display the URL of the safety information webpage, illustrated in Exhibit 4(b) similar to what the Physical Web application provides. The app does not display the irrelevant information of others in range devices, which aids in keeping the attention of the workers better than the Physical Web app. More importantly, the self-developed app can display various targeted alerts depending on where the worker is relative to the hazmat. The app defines an inner zone and an outer zone of the hazmat: the average radii of the inner zone and outer zone were set to be 1.5 meters and 5 meters, respectively. When the worker enters or leaves a zone, a corresponding alert is displayed on the interface of the app. Exhibit 4(d-f) display a few examples of such alerts.

Discussion and Results

The following is the comparison of the two systems in terms of the technologies they utilize, which is also summarized in Exhibit 5.

- The BLE beacon has considerably reduced power consumption and therefore it can be widely deployed. The ultrasonic ranging sensor requires a stable power supply and consumes more power than BLE beacon. However, the measurement precision of the ultrasonic ranging sensor is much higher than the BLE beacon.
- The smart mobile device is able to display detailed information to workers, and apps installed on the device can be designed to interact with workers. The use of a smart mobile phone as the receiving device requires Bluetooth wireless communication. The buzzer and LED screen are only able to deliver simple information and, thus, are usually set up as stationary devices connected to a power source.
- The data storage, processing, and analysis for the BLE beacon based system are mainly in the Cloud. Those for the Arduino based system are in the board. The Cloud has the superior capability of data storage, system analysis, and computation, thus making it a critical component of smart connected systems. The role of the Cloud cannot be substituted by an Arduino board.
- The BLE beacon based system relies on Bluetooth wireless communication, whereas the Arduino based system mainly relies on wired communication.
- Both systems require the efforts of programming. In this study, code for the BLE beacon based system was developed using the Estimote proximity beacon software development kit (SDK) in Swift with Xcode. Code for the Arduino based system was developed using the Arduino IDE in C. Overall, the coding effort for developing the BLE beacon based system was vastly more time consuming than that for the Arduino based system.

Exhibit 5. Comparison of the Systems by Technologies

	Arduino based system	**BLE beacon based system**
Sensor	Ultrasonic ranging sensor HC-SR04	BLE Estimote proximity beacon
Receiving devices	Buzzer, LED screen, smart phone	Smart phone
Data storage, processing and analysis	Arduino board	Beacon Cloud
Communication	Wired communication mainly	Bluetooth wireless communication
Development tool and language	Arduino IDE in C	Xcode in Swift

The technology evaluation of the two feedback systems indicated the BLE beacon based system would outperform the Arduino based system on the dimensions of interactivity, mobility, information richness, and connectivity. Yet, the development effort for a smart connected system is tremendously more than that for a simple Arduino based system. The evaluation of the strengths and limitations of the two respective systems within this study has suggested ways of improving the smart system design and development. These include, but not limited to: augmenting the distance measurement accuracy of BLE sensors, improving the modularity of the simple feedback devices, and protecting the privacy of each worker's smart mobile device(s) while collecting data to utilize the system.

Conclusions

This paper presented a study that built two feedback systems for enhancing transportation workers' awareness of risks when they are approaching and operating hazmat. The Arduino based system was quickly built and served as a reference for evaluating the development and technologies of the BLE beacon based system. The BLE beacon based system integrates strengths of multiple technologies, which include sensors with low energy consumption, the Cloud management platform, the powerful development environment of beacon applications, the mobility of receiving devices, and wireless communication. A qualitative comparison of technologies implemented between two risk awareness enhancement systems in terms of sensor, receiving devices, data management, communication, and development tool. Ongoing work of this study include testing and quantitative assessment of the smart connected system in simulated application scenarios, integrating it with the system dedicated to risk situation analysis, and improving the reliability of the system in certain situations. These include, but not limited to, the disruption of power supply to sensors, the ignorance of risk notifications by workers, and abnormal or complex motions of workers, which fail to trigger the system.

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References

An Overview of 49 CFR parts 172-173. *Hazmat Transportation Training Requirements.* Retrieved from US Department of Transportation, Pipeline and Hazardous Materials Safety Administration,. https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/docs/Hazmat_Transportation_Training_Requirements.pdf

Bureau of Transportation Statistics. (2017). Chapter 6: Transportation Safety. *2017 Transportation Statistics Annual Report*, US Department of Transportation.

Fruhling, A., Achutan, C., Medcalf, S., & Yoder, A. (2018). *Real-Time Emergency Communication System for HAZMAT Incidents (REaCH)-Phase I* (No. 25-1125-0005-111-1).

Godse, P. N., Long, S., Qin, R., & Xue, J. (2018). Data analysis for identifying high chance scenarios of hazardous material highway transportation incidents. In Proceedings of the International Annual Conference of the American Society for Engineering Management. (pp. 1-9).

Incident Statistics. (2018, April). Retrieved from US Department of Transportation, Pipeline and Hazardous Materials Safety Administration: https://www.phmsa.dot.gov/hazmat/library/data-stats/incidents.

Khaitan, S. K., & McCalley, J. D. (2015). Design techniques and applications of cyberphysical systems: A survey. IEEE Systems Journal, 9(2), 350-365.

Kim, K. D., & Kumar, P. R. (2012). Cyber–physical systems: A perspective at the centennial. Proceedings of the IEEE, 100(Special Centennial Issue), 1287-1308.

Lasisi, A., Bai, L., & Sun, Z. (2012). An Empirical Study on Risk Mitigation in Transporting Hazardous Material. In *IIE Annual Conference. Proceedings* (p. 1). Institute of Industrial and Systems Engineers (IISE).

Ma, Q., Wang, C., Lu, J., & Jiang, C. (2014). Development of an Integrated Emergency Management System for hazardous materials transport: Improve the transportation safety and enhance the efficiency of Emergency Response. 17th International IEEE Conference on Intelligent Transportation Systems (ITSC), 3046-3051.

Office of Hazardous Materials Safety. (2017). Top Consequence Hazardous Materials by Commodities & Failure modes, 2010-2014. Retrieved from US Department of Transportation, Pipeline and Hazardous Materials Safety Administration: https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/docs/hazmat-program-development/risk-and-regulatory-analysis/14291/ohmstc-data-update41217.pdf

Sha, L., Gopalakrishnan, S., Liu, X., & Wang, Q. (2008, June). Cyber-physical systems: A new frontier. In 2008 IEEE International Conference on Sensor Networks, Ubiquitous, and Trustworthy Computing (sutc 2008) (pp. 1-9). IEEE.

Mendez V.M., Monje C.A., White V. (2017) Beyond Traffic: Trends and Choices 2045—A National Dialogue About Future Transportation Opportunities and Challenges. In: Meyer G., Shaheen S. (eds) Disrupting Mobility. Lecture Notes in Mobility. Springer, Cham.

About the Authors

Jian Xue is a Master student, majored in Industrial Engineering, at Harbin Institute of Technology. She received her BE in Industrial Engineering from Harbin Institute of Technology, Harbin, China, in June 2018. Her current research interests include CPS (cyber-physical system), Cloud manufacturing and 3D printing. Her Master research topic is 'Intelligent scheduling optimization strategy for production lines based on cloud manufacturing'. Dr. Lizhong Zhao and Dr. Jihong Yan are her academic advisors.

Katherine Linville is a Ph.D. student in Engineering Management at Missouri University of Science and Technology in Rolla, Missouri. She received her MS in Engineering Management from Missouri University of Science and Technology, Rolla, Missouri, USA in May 2017. She also completed her BS in both Architectural and Civil Engineering in December 2012 from Missouri University of Science and Technology, Rolla, Missouri, USA. Her areas of interest are project management, data analysis, operations management, and mathematical modeling.

Yu Li is a Ph.D. student in System Engineering at Missouri University of Science and Technology. She obtained her M.S. degree in Systems Engineering from Missouri University of Science and Technology in 2019, and her B.S. degree in Engineering Management from Yichun University, China, in 2012. Her areas of interest include new transmission and maintenance technologies.

Pranav Nitin Godse is a Ph.D. student in Engineering Management at Missouri University of Science and Technology in Rolla, Missouri. He completed his MS in Engineering Management from Missouri University of Science and Technology, Rolla, Missouri, USA in May 2017 and BE in Electrical Engineering in May 2013 from Fr. C. Rodrigues Institute of Technology, affiliated to University of Mumbai. His areas of interest are operations management, engineering economics, statistics and data analysis.

Suzanna Long is Professor and Chair of the Engineering Management and Systems Engineering department at Missouri S&T. She has internationally recognized research expertise in critical infrastructure systems management focused on transportation/supply chain-logistics management, energy systems and organizational systems planning and effectiveness.

Jihong Yan is currently a professor at Harbin Institute of Technology, China. She received her Ph.D. degree from Harbin Institute of Technology, China, in 1999. Then she joined Tsinghua University (from 1999 to 2001), the University of Wisconsin (from 2001 to 2004) and Pennsylvania State University (from 2004 to 2005) as a postdoctoral researcher. Her research interests include industrial big data, prognostics, sustainable manufacturing, and intelligent manufacturing. She has authored and co-authored over 100 research papers and published 3 books. Two papers were ranked as the ESI highly cited papers. As a PI, Dr. Yan has worked on and accomplished over 20 projects in the sustainability and intelligent manufacturing related areas, funded by the NSF of China(NSFC), NSF-NSFC joint-project, National High-tech project, High-tech funding from industries, etc.

Lizhong Zhao received his Ph.D. and Master degrees in Mechatronics Engineering both form Harbin Institute of Technology, and his Bachelor degree in mechanical engineering from Harbin Institute of Technology, Harbin. Dr. Zhao is a senior engineer at the Department of Industrial Engineering, Harbin Institute of Technology, Harbin, PRC. His current research interests include intelligent manufacturing, decision analysis, and ergonomics.

Ruwen Qin is Ph.D., in Industrial Engineering and Operations Research, Pennsylvania State University, 2007. Dr. Qin obtained her M.S.E. and B.S.E. degrees in the majors of Spacecraft Design from Beijing University of Aeronautics and Astronautics, Beijing, China, in 2003 and 1999, respectively. Currently, she is an Associate Professor in the Department of Engineering Management and Systems Engineering at Missouri University of Science and Technology. Her research interests include data-driven statistical/stochastic modeling, dynamic optimization in service and operation, etc.